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STONE AGE

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Jürgen Richter

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Transformation analysis and systems-theory: from micro-scale lithic technical systems to macro-scale lithic ecosystems

Transformationsanalyse und Systemtheorie: Von kleinskaligen lithischen Einzelsystemen zu großskaligen lithischen Ökosystemen

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Abstract - Macroarchaeological questions on the long-term evolution of lithic technology have in recent years become a major focus of research in Palaeolihic archaeology. Big-picture accounts on lithic macroevolution have, however, either concentrated on assemblage-level variability, aggregated artefact-level patterns or millennial-scale trajectories of individual lithic systems. I here show that general systems-theory provides an alternative framework to tackle these questions with particular advantages with regard to macro-archaeological data. Based on lithic transformation analysis developed by Richter and others as well as *chaîne opératoire* insights, I offer a scalable perspective on higher-level dynamics in technological evolution. I present an ecosystem approach to lithic macroevolution and outline resultant research opportunities and key insights into why and how lithic systems co-exist and interact. This macro-scale perspective draws attention to the co-evolution and interrelationship of spatiotemporally associated technologies and investigates how such varied lithic systems are integrated into broader hominin-devised technological worlds. I argue that macroevolutionary questions on the lithic record can ultimately only be answered by understanding the configuration, assembly and long-term transformation of such technological worlds.

Zusammenfassung - *Makroarchäologische Fragen zur Langzeitevolution lithischer Technologie markieren seit einigen Jahren einen neuen Schwerpunkt paläolitharchäologischer Forschungen. Gesamtentwicklungen in den Blick nehmende Ansätze konzentrieren sich dabei jedoch in der Regel auf Inventar-bezogene Variabilitätsmuster, aggregierte Einzelartefakt-bezogene Eigenschaften oder auf sogenannte „Abstammungslinien" weitgehend isolierter lithischer Einzelsysteme. Der Beitrag versucht aufzuzeigen, dass die Allgemeine Systemtheorie ein alternatives Rahmenwerk zur Verfügung stellt, um diese Fragen zu adressieren und zudem den Umgang mit makroarchäologischen Daten verändert. Ausgehend von der lithischen Transformationsanalyse, die von Richter und anderen entwickelt wurde und zentralen Einsichten von* chaîne opératoire*-basierenden Untersuchungen, wird ein skalierbarer Ansatz zum Verständnis von übergeordneten Dynamiken technologischer Evolution vorgeschlagen. Es wird eine Ökosystem-Perspektive auf lithische Makroentwicklungen skizziert und dann die sich draus ergebenden neuen Forschungsmöglichkeiten sowie mögliche Schlüssel zum Wie und Warum der Ko-Existenz und Interaktion technischer Systeme besprochen. Diese höherskalige Perspektive lenkt die Aufmerksamkeit dabei auf die Koevolution und Wechselbeziehungen von raumzeitlich vergesellschafteten Technologien. So kann untersucht werden, auf welche Weise verschiedenartige lithische Einzelsysteme in umfassenderen technologischen Welten integriert werden. Dabei wird argumentiert, dass makroarchäologische Fragen an den lithischen Fundbestand nur dann zufriedenstellend beantwortet werden können, wenn die Konfiguration, Genese und Transformation solch umfassender technologischer Welten systematisch analysiert wird.*

Keywords - General systems-theory, macroevolution, lithic technology, technicity, technical infrastructure, systems-ecology
Allgemeine Systemtheorie, Makroevolution, lithische Technologie, Technizität, Technikinfrastruktur, Systemökologie

Transformation Analysis: a distinctively German approach to lithic technological organization and raw material management

Even though commonly overshadowed by dominant Anglophone and French modes of investigating Pleistocene lithic assemblages and technologies, transformation analysis (Germ. *Transformationsanalyse*; henceforth: TA) remains a powerful and distinctively German contribution to lithic studies. Developed in the late 90s and early 2000s by a group of scholars around Wolfgang Weißmüller (2003) and the jubilarian of this volume, Jürgen Richter (1997, 2005, 2006), and then carried on and further elaborated by their students and collaborators (Uthmeier & Richter 2005; Pastoors 2001; Uthmeier 2017; Bataille 2010, 2020; Bataille & Conard 2018), TA can be regarded as one of the few methodological proposals to date seeking to integrate the systemic analysis of lithic technology as pioneered by *chaîne opératoire* approaches (Boëda et al. 1990; Geneste et al. 1997; Geneste 2010; Inizan et al. 1999; Tixier 2012; Perlès 2018) with a dedicated research interest in hominin-ecology intersections, resource management and modes of landscape utilization including mobility and transport decisions (Kelly 1988; Binford 1980; Nelson 1991; Conard 2001; Uthmeier et al. 2008). The distinct version of TA championed by Richter can be regarded as a creative synthesis of site-oriented and raw material-centred "transformation-thinking" matured in Erlangen (Weißmüller 1996; 2003) and the landscape-archaeological perspective on past human economy, resource distribution and settlement organization (Ger. *Landschaftsarchäologie*) which took shape in Cologne's signature Neolithic studies at the same time (Zimmermann et al. 2004; Chabai & Uthmeier 2006). This particular formative background is important for assessing the principal contribution and legacy of TA in European Palaeolithic archaeology. Recalling this background is also crucial if we endeavour to gear-up, refine and possibly expand TA to tackle new or emerging questions previously not at the centre of the approach.

Following Richter's example in the early 2000s, I here attempt to re-synthesize TA's core rationale with emerging research questions and theoretical perspectives on the long-term evolution of Pleistocene lithic technologies (Kuhn 2020; Shea 2016; Goodale & Andrefsky Jr. 2015) in order to supply a novel framework for charting dynamics of lithic macroevolution. This redressing of TA *vis-à-vis* pending macro-archaeological questions requires the introduction of a small number of new concepts drawn from techno-anthropological, organizational and evolutionary thinking and the translation of TA's core tenets and insights into a new domain of investigation. I begin with a brief conceptual outline of lithic technology inspired by "transformation thinking" and other systems-views of human technical practice and then introduce what I call an "ecosystem perspective" on macro-patterns in lithic organization and evolution. This leads me to a new proposal for how to understand and study the emergence, composition and transformation of larger technological worlds made up of varied systems of lithic transformation.

Lithic technology: the systems-view in brief

Technology is a set of ordered relationships involving raw materials, artefacts, gestures, techniques, processes, routines, skill and knowledge. The latter entails at least 1) *practical or procedural knowledge* ("know-how" or *savoir faire*), 2) *embodied knowledge* (body schemata and body-utilization concepts including internalised gestures) and 3) *theoretical*

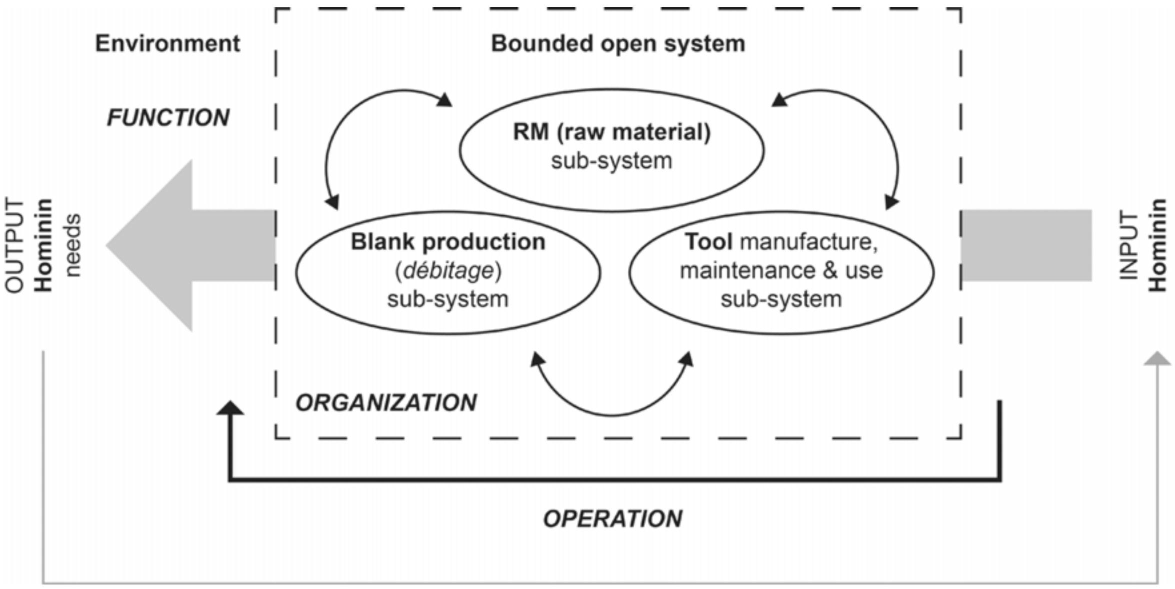

Fig. 1 Diagrammatic view of lithic system-level dynamics (scale: STS). *Organization*: structural and topological, exterior relations between effective lithic sub-systems. *Operation*: behaviour of the system totality as a function of the arrangement and "working together" of individual sub-systems. *Function*: services, utilities and possibilities of manipulation *vis-à-vis* the system environment (biophysical and social environment inhabited by hominins).

***Abb. 1** Diagrammatischer Blick auf lithische Systemdynamiken auf der Ebene kleintechnischer Systeme (STSs).* Organisation*: Strukturell und topologisch, äußere Beziehungen zwischen relevanten (effektiven) lithischen Subsystemen.* Operation*: Verhalten der Systemgesamtheit (STS) als Funktion der Einrichtung, Konfiguration und „Zusammenarbeit" von einzelnen Subsystemen.* Funktion*: STS-Dienstleistungen, Zweckmäßigkeiten („Nutzwert"), Manipulationsmöglichkeiten und Handlungsraum im Angesicht der spezifischen System-Umwelt (situierte biophysische und soziale Umwelt, die von Hominiden bewohnt wird).*

knowledge ("know-what" and "know-why" comprising more abstract reduction concepts, methods, *schémas opératoires* as well as cultural imperatives, preferences, visions and norms). TA's key notion of "conceptual reservoirs" (Ger. *Konzeptreservoirs*) describes the content and historical legacy of all of these three knowledge-vectors (Weißmüller 2003; Bataille 2020) and thus the generalized possibility-space of deploying particular lithic technologies and their corresponding artefacts and activities at a given time and place. As a set of ordered (mostly technical) relationships, lithic technology can be qualified as a *purposed open system* with heterogeneous constituent parts. The system is "open" because it exchanges energy and matter with its environment and upholds direct physical contact with the latter – e.g. through instrumental tool-behaviours such as cutting, sawing and scraping (Lepot 1992; Boëda 2013; Rabardel 1995). The system is "purposed" because lithic technologies are prosthetic devices (Gehlen 1956; Kapp 1877; Stiegler 1998; Sigaut 2007; Guchet 2018): they facilitate acting upon the world, respond to behavioural, social and cognitive needs, and provide significant functionalities and behavioural affordances otherwise not available (either in quantity or quality). In this sense, lithic technologies are always *goal-oriented*, they are directed to future behaviour(s) of their hominin users and hence ineluctably have "finality" (see Ropohl 2009 for the problems of rejecting user-oriented views of system-finality). This also implies that there is always at the very least a residual mark of intentionality which frames, filters and organizes the set of ordered relationships in question – a lithic system cannot be said to be devoid of intention even if the respective intentionalities are "malleable", "emergent" or "distributed" rather than strictly preconceived (purposiveness is not binary). Technical systems are arguably distinct from other systems in this regard.

The systemic view of lithic technology draws attention to three axes of description and orderliness: each system is characterized by a) the function or range of functions it supports,

b) its (mode of) operation (how the system behaves and "works") and c) its organization (compartmentalization, (infra)structure and the nature/role of constituent parts; Fig. 1). The problem tabled here is mereological and as such concerns the identification and specification of part-whole relationships as they pertain to lithic systems (recognizing the identity of such systems based on large numbers of "mixed" lithic artefactual remains composed in more-or-less contaminated archaeological assemblages is part of this problem). To reduce lithic technological complexity to its tangible material dimensions for a minute, lithic systems can be represented as specifically configured raw material-blank-tool systems with a differentially directed yet generally irreversible reduction stream (lithic exploitation is inescapably subtractive). Such technical systems from the hominin deep past can be, and already have been – more-or-less cognizantly or explicitly at least – studied and described by employing TA. The following section briefly illustrates how this is commonly achieved before turning to the big picture question of long-term technological evolution.

Qualifying the articulation of lithic systems via TA

The fundamental starting hypothesis of TA is that lithic raw materials (RMs) matter for the assembly and latent design of technical systems. TA further posits that differences in RM quality, workability and geometric properties as well as their relationship to specific ways of organizing lithic knapping (operational sequences) should be analysed on relevant human scales – that is, in relation to recognizable and relatively easily perceptible (macroscopic) peculiarities of RMs as they are encountered in hominin lifeworld contexts. This hypothesis can be tested by sorting all lithic artefacts – cores, blanks and tools – of a given lithic assemblage into raw material units (RMUs) with the ultimate goal to further resolve these macro-units on the level of individual "workpieces" (WPs; Ger. *knollengleiche Werkstücke*) referring to original RM-volumes, e.g. pebbles, nodules and flakes (Richter 1997; Weißmüller 2003; Bataille 2020; Geyer 2013). The basic idea is that for each WP, one can then examine and characterize the associated operational sequence(s) and, equally importantly, determine any missing reduction elements in order to assess RM-related patterns of lithic export. Inversely, artefacts that cannot be sorted back into WPs with evidence for in-place core preparation and/or reduction inform on past import decisions. If RMs form an integral part of the latent design of lithic transformation systems, differences in the treatment of RMs should be detectable on the scale of RMUs or WPs and these differences should make sense in light of the reconstructed blank-tool relationships for the same RMs. In other words, TA provides the analytical resolution and capacity to address the question of whether lithic RMs influence blank production and tool confection/use as well as their interdependencies within the same reduction stream or broader RM-context. By comparing the articulation and operational make-up of RM-blank-tool systems across RMUs and WPs, it is thus possible to determine whether and on which level RMs are an effective category in the system, and, relatedly, whether technical systems are rooted in or adapted to particular RMs (Hussain & Will 2021). Based on experimental knowledge on the interaction between RM-properties and requirements, knapping processes and production goals, we can derive hypotheses on the type and strength of relationships defining the nexus of RM-choice, blank production and tool mobilization, and accordingly learn about RMs as system components. The possible non-consequential status of select RMs *vis-à-vis* their associated lithic operational sequences may in turn indicate that the RM in question is not an effective category of latent design, thus opening up alternative perspectives on the documented choice of RMs: i) the operation of the lithic system(s) in question does not in principle depend on specific RM-properties (or only generalized properties such as granularity), possibly because its purpose is precisely to relax RM-blank/tool relations; ii) the availability and provisioning mode of RMs interfere with RM-choice; and/or, interestingly, iii) the non-consequentiality of RMs hints at cultural-normative rather than mineral-operative reasons for RM-choice.

Based on this foray into RMs as a lithic systems-component, we can stipulate that studying lithic technology from a systems-theoretical perspective involves at least the analysis of structural relationships between three broad sub-system domains: 1) RM acquisition, choice and transport, 2) handling of selected RM-volumes and their organized blank exploitation, and 3) transformation, use and maintenance of the supplied blanks as modified or unmodified tools, including their differential transport across the landscape. As outlined above, TA is particularly suited to elucidate the RM systems-component and its articulation (or not) with blank production modalities, while blank production and volume/core management sub-systems have been most thoroughly studied and described by *chaîne opératoire*-based techno-economic research (Perlès 1980; Bon 2002; Pelegrin 2011; Delagnes 2010; Valentin et al. 2014; Pesesse 2018). The methods and conceptual language to understand the systems-components related to making and using lithic tools are in turn provided by holistic use-wear studies (Rots 2004; Marreiros et al. 2020), UTF and working-stage analysis (Albrecht & Müller-Beck 1988; Lepot 1992; Richter 1997; Jöris 1997; Pastoors 2000; Soriano 2000; Forestier 2010; Boëda 2013; Tafelmaier 2020; Forestier & Boëda 2021) as well as lithic design theory (Bleed 1986; Nelson 1997; O'Farrell 2004). Within this landscape of labour division, TA yields the unique promise to contextualize the arrangement of these systems-components within broader hominin ecologies and land-use systems beyond the artefact-centric (and to this effect non-systemic) lens of Anglophone organization of technology approaches (Binford 1989; Nelson 1991; McCall 2020), and to empirically assess rather than prejudge the causal involvement of RMs in structured processes of lithic reduction, tool-making and cutting-edge mobilization.

To generalize, the systems-view on lithic technology offers a scale-variant account of whole-part relations with particular organizational, operational and functional characteristics eclipsing the mere sum of observed material (lithic) artefacts. The respective part-whole relationships provide structural (and typically hierarchical) depth with multiple levels of organization associated with specific system-level qualities. Each system-level totality emerges from the interactions of its constitutive parts, the relevant sub-systems, which can in turn be analysed as purposed lower-level systems composed of yet another level of sub-systems. On each system-level, we can thus identify and describe interior and exterior relations: interior relations specify the structural connection of subsystems (organization) ensuring that the system can properly "operate" and thus fulfil its systemic "finalities" (function), whereas exterior relations detail how the system is deployed in and interacts with its environment. This is thus for example the place to examine how the recognized system finalities play out in hominin (quotidian) affairs, e.g. larger adaptive systems tied to particular landscapes, climates, resources and affordances of movement.

For the analysis of broader lithic sub-systems such as RM choice/handling, blank production and tool construction/utilization, it is further useful to distinguish between *vertical* and *horizontal* relationships in order to determine their organization and operation. Vertical relationships are primarily chronological and refer to the sequencing and scheduling of technical operations and artefact provenances within an unfolding reduction stream. With regard to blank production sub-systems, for example, verticality pertains to meaningful reduction stages, and system-inherent rhythms and possibly cycles of blank supply, either ordered according to blank type or providing a range of variegated blank types (to be further described). Vertical

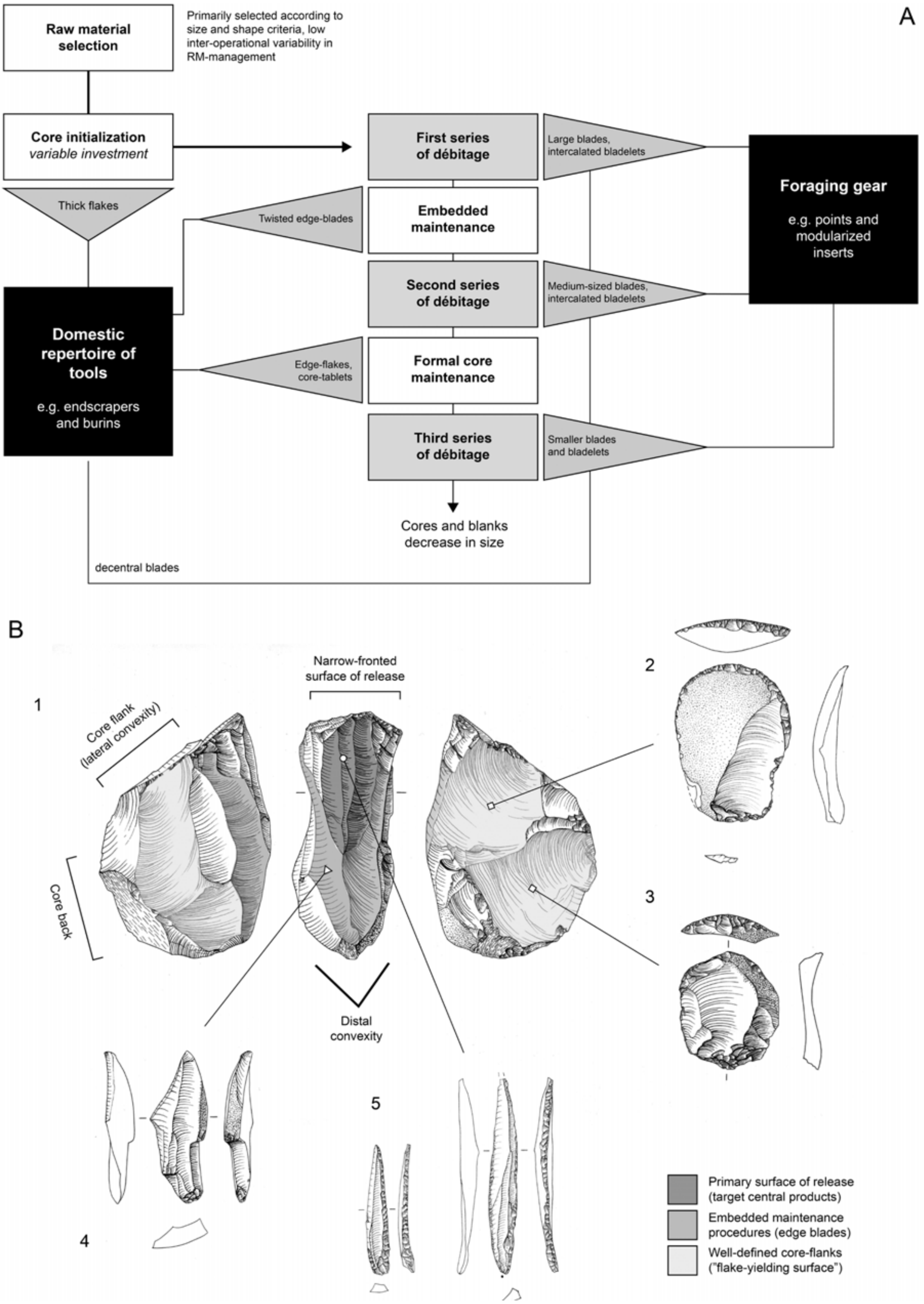
A
Raw material selection
Primarily selected according to size and shape criteria, low inter-operational variability in RM-management
Core initialization
variable investment
Thick flakes
First series of débitage
Large blades, intercalated bladelets
Foraging gear
e.g. points and modularized inserts
Twisted edge-blades
Embedded maintenance
Second series of débitage
Medium-sized blades, intercalated bladelets
Domestic repertoire of tools
e.g. endscrapers and burins
Edge-flakes, core-tablets
Formal core maintenance
Third series of débitage
Smaller blades and bladelets
Cores and blanks decrease in size
decentral blades
B
Narrow-fronted surface of release
1
Core flank (lateral convexity)
Core back
Distal convexity
2
3
4
5
Primary surface of release (target central products)
Embedded maintenance procedures (edge blades)
Well-defined core-flanks ("flake-yielding surface")

Fig. 2 Examples of STS-level lithic systems-analysis based on the Early Ahmarian assemblage of Al-Ansab 1, Southern Jordan (Early Upper Palaeolithic, ca. 36–39,000 cal. BP; Hussain 2015; Richter et al. 2020; Parow-Souchon et al. 2021). A: idealized procedural map of lithic technology at al-Ansab1 showing how raw material selection and management are articulated with a structured, fully integrated blade/let-oriented débitage system and a distinct topology of more-or-less well-defined blank production goals tied to broader tool domains. B: schematic overview of the organizational relationships within the al-Ansab 1 core-blank-tool system (for the sake of simplicity, vertical and horizontal relations are projected onto a single axis). 1) Architecture (latent design) and organizational structure (narrow-fronted, acute-angled unidirectional, V-shaped single-platform cores with well-defined (functional) core flanks) resulting in a distinct system of surface convexity management; 2–5) blank-tool conversion dynamics with blanks deriving from different core surface locations and temporal positions within the reduction stream supplying the matrices for distinct groups of lithic tools (2–3: thick, often cortex-bearing endscrapers on core-flank flakes; 4: larger and often steep, slightly twisted and/or off-axis blades transformed into burins, truncations or endscrapers; 5: central convergent or parallel-pointed blades and bladelets modified with marginal lateral and/or distal retouch or adapted to el-Wad points).

***Abb. 2** Beispiele und Möglichkeiten von lithischer STS-Analyse basierend auf dem Steinartefaktinventar des frühen Ahmarien von Al-Ansab 1, Südjordanien (Frühes Jungpaläolithikum, ca. 36–39,000 cal. BP; Hussain 2015; Richter et al. 2020; Parow-Souchon et al. 2021). A: Idealisierte Prozess-Kartierung der lithischen Technologie von Al-Ansab 1. Rohmaterialselektion und –management folgen einem strukturierten, voll integrierten klingen- und lamellenorientierten Abbausystem und einer Topologie von mehr oder minder gut definierten Grundformproduktionszielen, welche wiederum an allgemeine Werkzeugdomänen gebunden sind. B: Schematische Übersicht der organisatorischen Zusammenhänge innerhalb des Kern-Grundform-Werkzeug-Systems von Al-Ansab 1 (der Einfachheit halber wurden vertikale und horizontale Beziehungen (siehe Text) auf eine einzige Achse projiziert). 1) Kern-Architektur (latentes Design) und organisatorische Struktur (Kerne mit schmaler Abbaufront, spitzwinklig und unidirektional, V-förmig zugerichteten Abbauflächen mit einer Schlagfläche und gut definierten (funktionalen) Kernflanken) fundieren ein spezifisches System der Oberflächenkonvexitätskontrolle. 2–5) Grundform-Werkzeug Umwandlungsdynamiken basierend auf Grundformen, die von verschiedenen Kernoberflächenbereichen und Kernabbaustadien stammen und als Matrix (Frz.* support) *für unterschiedliche Werkzeuggruppierungen auftreten. (2–3: dicke, meist kortextragende Kratzer an Kernflankenabschlägen; 4: größere und oft steile, leicht gedrehte, asymmetrische und „off-axis" Klingen, welche zu Sticheln, Endretuschen oder Kratzern weiterverarbeitet wurden; 5: zentrale konvergierende oder parallel spitz-zulaufende Klingen und Lamellen, die mithilfe von marginaler lateraler oder distaler Retusche modifiziert und bevorzugt zu el-Wad Spitzen transformiert wurden).*

organization, powered by the structured management of exploitable volumes, in this way filters and thus pre-structures the artefact "output" at different segments of the reduction process. Horizontality, by contrast, bears upon the constitutive and technical relationships within any given temporal segment of reduction. A classic example is the specific surface topology of cores at particular reduction stages with regard to the extraction of different blank types and the enabling relationships between similar or different types of blanks from the same surface area or similar convexity configurations. System-defining relationships are frequently found at the intersection of horizontal and vertical patterns of lithic organization, e.g. when blank types of particular extraction localities are selected to serve as preferential matrices for particular types of (retouched) tools. A general question is whether the finalities of sub-systems within these systems align, and hence support each other, or, alternatively, not, for instance when tool confections systematically override the inherited features and properties of foregoing blank production outcomes. The totality of significant exterior and interior system-relations provided as vertical and/or horizontal patterns of organization can then be understood as a given system's technical infrastructure. Describing and understanding a lithic system entails specifying which artefacts are the system's finalities, specifying the place of each of these artefacts within the system's technical infrastructure and providing an account of how this organization is procedurally brought into being, which in the context of lithic technology normally requires at least the designation of interrelated knapping gestures, directionalities of removal and problem-oriented preparatory procedures (explicit/formalized or embedded) to create and maintain the necessary convexity structures, changing over the course of reduction or not.

Although the description of lithic systemic functioning is not arbitrary, there is also not necessarily a single adequate description of the interplay of a system's operative, organizational and functional dimensions. The overarching problem is that the delineated sub-systems need to be broad and general enough to ensure that their interior and exterior relationships can fruitfully be compared across systems without assuming too much about the detailed make-up and operation of lithic systems in general. The challenge, in other words, is to acknowledge and analytically exploit some of the universal qualities of lithic technical systems without over-universalizing organizational structures and performance characteristics, which are in fact context-specific and thus earmark only a subset of all lithic systems. TA, too, sometimes falls into this trap, especially when analysing the representation of precast operative stages by signature/surrogate artefacts (Ger. *Stellvertreter*) in a set order without spending much time to unpack their interior relationships or considering the differential distribution of technical operations across the reduction stream (including, e.g. possibilities of "intercalation", etc.). This does not necessarily render the results of TA problematic but it does introduce a good dose of systemic idealization, preventing a detailed comparison of the overall spatiotemporal configuration of the precast operative stages within the overall lithic transformation process. Focusing on RM-blank-tool systems – at least in the realm of *débitage* technology – and considering each of these components as heuristic sub-system domains to build up systemic understanding may be a feasible way to circumvent these issues while considerably expanding our understanding of lithic technology (Fig. 2), especially its situated organization and operation, by drawing on general systems-theory (Bertalanffy 2003; Mueller 1996; Rapoport 1968; Hofkirchner & Schafranek 2011), and thus join forces with the bigger project of systems science in statu ascendi.

Lithic ecosystems: the systems-view extended

With this basic account of lithic systems in mind, we can reframe the problem of long-term technological evolution in systems-theoretical terms. The basis of my suggestion is the observation that current research on long-term lithic evolution is either broadly artefact-centric, commonly generalizing from assemblage-level lithic variability to detect directional change or diversity spikes without considering system-level patterns of organization (Kuhn 2020; Goodale and Andrefsky Jr. 2015), or seeks to chart the evolution of lithic systems in terms of system-lineages (Boëda 2013; Weyer et al. 2022). These approaches either neglect system-level dynamics altogether or they concentrate on millennial trajectories of isolated technological systems or system-families. In the latter case, the focus of description and analysis remains largely intra-technological, even though changes in intra-system make-up are compared across vast swaths of time and space. From a systems-theoretical perspective, however, there is good reason to suspect that the key for better understanding the macroevolution of lithic technology is to be found in even higher-level processes of system assembly, interaction and disintegration – and not in the secluded examination of select individual systems on the scale of RM-blank-tool systems. In other words, I suggest to shift scholarly attention from intra-technological analyses (original domain of micro-scale lithic studies) to inter-technological investigations (proper domain of macro-scale lithic studies) in order to tackle big picture questions of lithic evolution without inadmissibly flattening the observational complexities of the lithic archaeological record.

The key idea here is drawn from organizational research on technological evolution, which has long recognized that technologies do not evolve in isolation but rather emerge and develop in concert with other technologies (Arthur 2010; Adomavicius et al. 2007; Liu et al. 2015). The best-known example for the interdependent co-evolution of technology is provided by the PC: personal computing technology developed in sync with other supportive or complementary technologies such as computer screens, PC mice, keyboards (in the West most notably with the QWERTY layout), printers as well as network and internet technology. Careful investigations of the involved relational

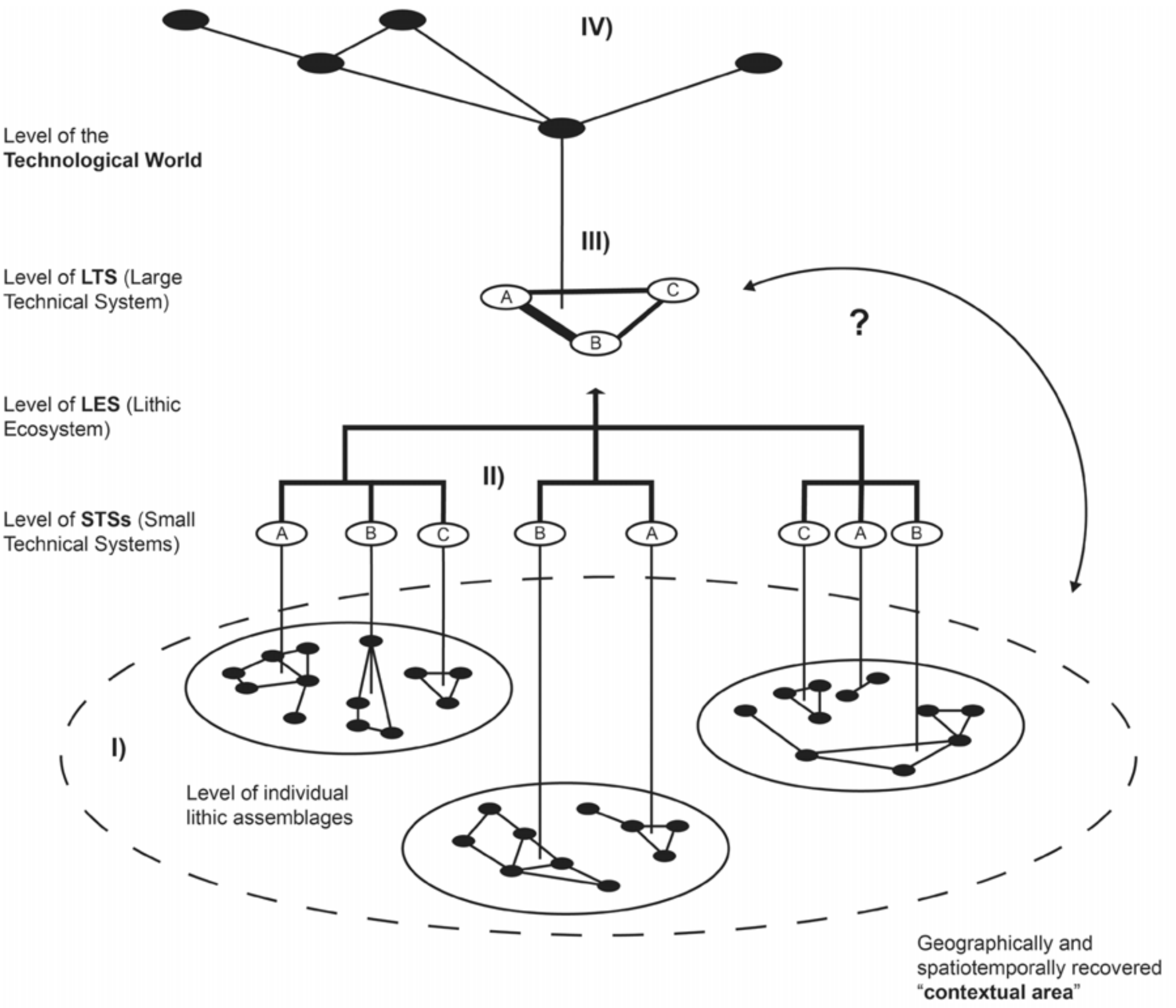

Fig. 3 Diagrammatic view of primary levels of organization within a broader technological world (TW). Small black dots represent individual artefacts or technologically relevant groupings of lithic artefacts; capital letters denote specific small technical systems (STSs) with distinct system-level qualities; large black dots represent large technical systems (LTSs).
I) Lower level of lithic organization: assemblages associated with individual sites/layers embedded in a geographically explicit landscape; II) Medium level of lithic organization: formal (named) and informal lithic systems (STSs) retrieved from technological micro-analysis; III) Upper level of lithic organization: ecosystem of STSs in a given spatiotemporal context (macro-analysis of inter-STS relations), yielding specifically configured LTSs; IV) Supra-level of lithic organization: arrangement of LTSs across multiple spatiotemporal settings. The in this way circumscribed technological world (TW) is defined by the transregional adjacency and broad penecontemporaneity of the partaking LTSs.

***Abb. 3** Diagrammatischer Überblick der primären Organisationsebenen innerhalb einer erweitereten Technologischen Welt (TW). Kleine schwarze Punkte repräsentieren einzelne Artefakte oder technologisch relevante Gruppierungen von lithischen Artefakten; Großbuchstaben denotieren spezifische kleintechnologische Systeme (STSs) mit distinkten Eigenschaften auf der Systemebene; große schwarze Punkte repräsentieren großtechnische Systeme (LTSs). I) Untere Ebene der lithischen Organisation: Diskrete Inventare, die mit individuellen Fundstellen/Schichten assoziiert sind und in eine geographische explizite Landschaft eingebettet sind; II) Mittlere Ebene der lithischen Organisation: formale (benannte) und informelle kleintechnische lithische Systeme (STSs), die aus der technologischen Mikroanalyse gewonnen werden; III) Obere Ebene der lithischen Organisation: Ökosystem der Gesamtheit von STSs innerhalb eines gegebenen raumzeitlichen Kontexts (Makroanalyse von Beziehungen zwischen STSs), die in der Identifizierung und Charakterisierung eines großtechnischen Systems (LTS) resultiert; IV) Übergeordnete Ebene („Supra-Level") der lithischen Organisation: Anordnung und Konfiguration von multiplen LTSs über mehrere raumzeitliche Kontexte. Die dabei umrissene Technologische Welt (TW) ist über die transregionale Nachbarschaft und Quasi-Zeitgleichheit aller teilnehmenden LTSs bestimmt.*

dynamics have shown that these technologies have mutually entrenched each other into their present evolutionary pathway(s) (David 1997; 1985; Arthur 2010). The appropriate context of long-term technological evolution is thus larger-scale technical ecosystems (Adomavicius et al. 2007). This "ecosystem approach" to technological evolution regards co-existing technologies as a key selective and adaptive context for individual technologies to take shape. The ecosystems-view of technological evolution is fully consistent with a broader systems-perspective since the ecosystem effectively represents a scaled-up system totality in which original individual technical systems assume the role of sub-systems. The systems-perspective allows us to ask for the organization, operation and function of the technical ecosystem as a whole and thus informs about constitutive intra-system dynamics.

To formalize this approach for lithic research, it seems useful to first distinguish between ordinary or small technical systems (STSs) on the scale of named lithic technologies such as the variants of Levallois, Quina, Discoid, Pucheuil, S.S.D.A., the variously described volumetric or facial blade production technologies, burin-core and "carinated" core technologies or bipolar reduction variants, and large technical systems (LTSs) which contain multiple such smaller individual lithic systems and thus form a specific lithic ecosystem (LES). The term "large technical systems" is co-opted from the work of technological historian Thomas P. Hughes, even though he originally developed the concept to describe technological networks of enormous proportion and complexity as they have become symptomatic for the modern era of "Big Technology" (Hughes 2011; Mayntz & Hughes 2019). The purpose is not to import this latter more nuanced historical signification but rather to offer an intuitive shorthand for higher-level system totalities composed of traditional archaeological STSs.

We may then say that the procedural-embodied, user-oriented and theoretical, maker-oriented knowledge perpetuated by LTSs feed into a *technological world* (TW) limited only by the extent of spatiotemporal connectivity of hominin technological makers and users (Fig. 3). This "world" promotes certain technical practices and not others and certain ways of seeing and being (including how problems are perceived and solved) but also socializes and habituates its inhabitants to particular technology-mediated forms of life. Growing up in pre-furnished technological worlds has implications not only for modes and trajectories of technical knowledge transfer (Tully 2003) but also for the organizational possibilities of adjusting inherited STSs, co-opting them for new tasks or re-structure the relationships between them, let alone developing new STSs for particular sought-after technical ecosystem-services. Weißmüller's notion of the "concept reservoir" (Ger. *Konzeptreservoir*) highlighted above as an integral component of TA is best understood in relation to such technological worlds: as the totality of known and easily divisible (latent) technical concept-solutions in any specific hominin "contextual area" (Weißmüller 2003; Richter et al. 2012). Contextual areas in this sense are hence never given but must be found in empirical analysis by taking into account the socioecological and geographic background of hominin technical behaviour.

The notion of the *technological world* (TW) clarifies what the "technological condition" of human existence entails (Hörl 2011; Stiegler 1998). As evolved habitual-compulsory technological beings (Shea 2016), the TW becomes the precondition, raw material and motor of human evolution. Hominins are shaped by their TWs before they have a chance to shape them, which in turn re-configures the long-term evolutionary pathways hominins find themselves in (Hussain & Will 2021). Stiegler (1998) has called this the "pharmacological condition" of our evolved human nature: TW and technical ecosystems change the dynamics of evolutionary processes, they bring "curse" and "salvation" at the same time – technology opens up previously unattainable possibilities, affordances and action-spaces but it coevally closes and/or considerably interferes with other options and imaginative horizons or significantly alters cost-benefit relations (Hussain 2018). The technological world thus equips us with a macro-archaeological lens to chart alternative, deep-historical anthropotechnological constellations, and thus to explore the alterity of hominin technicity across unique temporal and spatial scales.

Concrete LESs can be studied in analogy to ordinary lithic systems (STSs) but a focus on their organization may initially be insightful. From an organizational perspective, we can ask how many STSs make up the ecosystem, how important different STSs are for that ecosystem and how the enumerated STSs interact with each other (if at all) – i.e. what larger roles they fulfil in their LTS. To formalize and illustrate technological roles, we can draw on Arthur's (2009, 174f.) elaboration of "opportunity niches" – the tendency for technologies to fill roles or provide services that are in demand, either by their users or by other co-existing technologies. In terms of LTS infrastructure-relations, any given STS can directly support the operation or function of another STS (synergy, adaptation), it may complement that other STS, it may fill broadly similar or even redundant roles by other means or not (competition, resilience), or it may strongly diverge from the operation-function nexus of (most of) its co-existing STSs (specialisation, monopolization). This not only means that we can make direct use of insights gained by TA and other system-oriented approaches from the lithic micro-level to inform our understanding of macro-level LTS dynamics, we can specifically incorporate basic and well-established observations on STS-specific RM-ecologies, the relationship between technical investment and blank productivity, ramification potential, blank output affordances, the predictability of outputs as well as the overall transportability and situational transformability of supported blanks/tools (Meignen et al. 2009; Bourguignon, Delagnes, and Meignen 2006; Delagnes & Meignen 2006; Kuhn 2020; Bourguignon et al. 2004; Hiscock et al. 2009; Delagnes 2010; Mathias and Bourguignon 2020; Delagnes and Rendu 2011). Some important groundwork on lithic inter-*débitage* relations (Perlès 1980; Geneste 2010; Bourguignon et al. 2006; Delagnes et al. 2012; Faivre et al. 2017; Carmignani 2017; Chevrier et al. 2018), and especially on *débitage-façonnage* interstices (Boëda 1995; Soriano 2000; Brenet & Folgado 2009; Brenet et al. 2014), has already been conducted. A systems-theoretical perspective can help to systematize, formalize and ultimately mobilize this knowledge for the comparative analysis of STS-roles within larger lithic ecosystems in their chronospatial contexts. This shift in orientation generally aids in transitioning from the "what" question of assemblage-level technological analysis and STS-identification to the fundamental "why" questions of ecosystem-level STS-assembly, relational configuration and functioning.

Drawing on TA, we can for example ask whether synergies between RM-choice and the organization of blank production deliver blank spectra and/or tool sets complementary to other co-existing RM-*débitage* system compositions or *façonnage* systems, and, relatedly, whether stronger formalized (named) STSs are associated with better defined RM-*débitage* relations than documented informal blank production options. Answering these and similar questions helps to explore the extent to which co-existing STSs tap into a larger technical landscape of "labour division" (technical division of labour: TLD). TLD, accordingly, can occur on different levels of STS-organization and functioning: it may pertain to the choice and exploitation of raw material sources (e.g. local vs. non-local, low quality vs. high quality, large matrices vs. small matrices), to the range, trait-structure and morphometrics of obtained plain blanks and/or the tool-making and re-sharpening/re-working potential of said lithic blanks (structured blank-tool relations or not). These various domains of STS-operability can be compared across LES-inhabiting STSs with regard to the infrastructure-relations/basic types of technological roles outlined above, resulting in a general map of "opportunity niches" (Arthur 2010) filled by individual STSs. Mapped opportunity niches help us to qualify the basic technical work of specific STSs in their respective LES, and thus to infer LES-wide patterns of TLD – this broadly corresponds to the delineation and description of LES-level technical infrastructures which are key for understanding LTSs. These patterns, in turn, can then be contextualized with the hominin ecologies in which they make their appearance, especially site-specific activity profiles and landscape-wide behavioural patterns such as mobility (Turq et al. 2013). We would expect that the full register of STS-supplied outputs, behavioural affordances and system finalities in a given LTSs articulates in some way with human needs enacted on the respective LTS-corresponding landscape-scale (which would effectively engender an integrated, complex human-LTS system of substantial spatiotemporal scope and evidential depth). The articulation of LTSs and human mobility and subsistence systems hence discloses yet another layer of relational analysis – yet, the ties in question cannot be precast simply as "correlative" or" implicative" – there is not necessarily a one-to-one link between specific LTSs and specific mobility-subsistence configurations.

The functionality of integrated LTSs derives from their corresponding technical infrastructure, especially the LTS-specific TDL. Soriano (2000) has for example shown how inter-STS relations between relatively simple, weakly-predetermining flake production systems and bifacial tool systems change at the Lower Palaeolithic–Early Middle Palaeolithic interface in tandem with changes in hominin land-use, with flake production systems serving to supply local, situational-stationary functions based on relaxed RM-requirements at particular localities and bifacial systems designed to be highly mobile and provide long-term, future-oriented functions of "delayed return" but elevated reliability. *Débitage-façonnage* relationships hence develop into complementarity and synergy with regard to the use and management of RMs and the scheduling of activities on the broader landscape. Boëda (1995) has argued that in the Micoquian of Kůlna cave (Czech Republic), by contrast, the relationship between *débitage* and *façonnage* is not complementary but at least in part based on *functional equivalency*, so that both systems feed the same register of cutting-edge configurations. From a macro-evolutionary ecosystem perspective, the Kůlna Micoquian thus appears to be an expression not necessarily of pronounced TDL but instead reflects the diversification of operational pathways to achieve broadly comparable outcomes and system finalities, perhaps as a risk-mitigation strategy since functional redundancy within larger systems is generally though to bolster system resilience. Both of these examples also draw attention to possible *power-relations* and horizontal hierarchies between STSs. STSs can be more or less *central* to the operation and function of their LES – they can be "focal" or "distal" to the total system's performance – and they can be more or less indispensable/vital for the behaviour and functionality of the LES. A given STS may be an optional add-on to a set of indispensable, nearly-always-encountered core technologies. This optionality may be rooted in the need to support the core STSs, for instance with regard to their blank productivity, with or without increasing system redundancy, or it may be based on the need to supply additional, typically situational, functions that differ from the core STSs' finalities (weak/contingent complementarity and/or synergy). Enslavement occurs when focal STSs unilaterally shape the behaviour and output of more distal STSs. The core technologies can then also be rendered "salient" STSs. These types of structured intra-LES relationships and their attendant sub-system trade-offs provide key information for answering why, when and how particular STSs were deployed in different landscape, subsistence and mobility contexts of the hominin deep past. The ecosystem perspective on technological evolution, in other words, allows us to productively connect nascent knowledge on the benefits and shortcomings of individual lithic technical systems (STSs) with knowledge on the composition of site-specific, regional or continental lithic ecosystems (LESs) to better understand the link between hominin technicity and landscape-use. This, in my view, provides the only adequate scale and unit of analysis to address perennial questions of adaptation and long-term evolution. Lithic technology is an ecosystem and in order to understand why and how it changes over millennia we have to examine its organization, operation and function and link it to changing hominin lifeways.

Conclusion

A systems-view on lithic technology can help mapping, and ultimately comparing, long-term dynamics of technological evolution without retreating to the polarized, and often misleading, or at least incomplete, positions which have taken root in Palaeolithic archaeology in the aftermath of the Binford-Bordes debate. As I have tried to unpack elsewhere – and as I believe is very much in line with the convictions of the jubilarian of this volume – these positions often mistakenly presume that the lithic variability that fuels evolutionary processes equates artefactual variability. The argument I have attempted to unfold on the foregoing pages, by contrast, seeks to show that lithic variability can only be adequately dealt with if a hierarchical, levels-of-organization-sensitive approach to the evidence is adopted. Systems-theory provides one such perspective and offers the formal framework necessary to resolve basic artefactual variability encountered on the assemblage-scale into higher-order patterns of organization. I have argued that only the in this way recovered systems-variability of lithic technology is suitable for answering macro-evolutionary questions of large spatiotemporal scales. Analysing this systems-level variability, and ultimately resolving it, within larger lithic ecosystems provides a unique window into the "self-organizational" properties of the larger technical environments or ecologies in which various hominins lived in and adapted to. Scalable lithic systems-analysis thus stands to make a critical contribution to the characterization and apprehension of the "human niche" (Fuentes 2017). The empirical basis for this exciting promise, however, remains our knowledge on the properties of individual lithic systems as investigated by approaches like TA and *chaîne opératoire* analysis.

Acknowledgements

I dedicate these reflections to Jürgen Richter in celebration of his professional and academic life. At least to me, Jürgen has frequently expressed his restrained disappointment that transformation analysis has not been further developed by the next generation of lithic scholars in Germany or elsewhere, and, perhaps also because of this, today remains a largely neglected and marginalised approach even within European lithic research. This contribution is my humble attempt to show that this must not be the last word, and much can in fact be done based on basic work conducted in the late 90s and early 2000.

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